The Advantages of New Vantages for Earth Science — Earth Observation Mission Vantages: Options

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Abstract– All observing missions must perform certain basic functions. Among these, missions observe by physically interacting with the environment, and must place themselves at an appropriate vantage to obtain these observations. This paper examines current and proposed vantages used for Earth science observation missions. The paper identifies key aspects of value for these vantages and uses these aspects to suggest other vantages that may be of interest for future Earth observation missions. For space missions the three key aspects are (1) range/continuity of coverage, (2) lighting/time of day, and (3) ground-track geolocation. For example, the Deep Space Climate Observer uses the Sun-Earth Lagrange point to achieve distant/continuous coverage with constant, near noon lighting. The advance of technologies such as solar sails, long-duration balloons, and unpiloted air vehicles will enable the consideration of vantages not currently possible. The author hopes that an improved understanding of the value for Earth science of new vantages will facilitate the identification, development, and adoption of new mission capabilities to achieve these vantages.

I. Introduction

The author recently completed a thesis for a Master's Degree from the Massachusetts Institute of Technology.[1] As part of this thesis, the author systematically analyzed generic functions common to all Earth observing missions. This paper focuses on the vantages used to acquire space-based observations.

All missions, whether for space-based remote sensing or Earth-based *in situ* sensing, observe by physically interacting with some aspect of the environment, and must place themselves at an appropriate vantage for these interactions. Space-based sensing involves spacecraft in Earth orbit or beyond. The scopes of these observations are inherently global.

This paper identifies three key aspects of value for the space vantages used for Earth science observation missions. It describes these three aspects and uses them to suggest other vantages that may be of interest for future space-based Earth observation missions.

II. Aspects of Space Vantage Value

For space missions the three key aspects of value for space vantages are:

(1) range/coverage,
(2) lighting/time of day, and
(3) ground-track geocoverage or geolocation.

In identifying example missions that utilize these different approaches, the author drew upon the work of Kramer.[2]

A. Range/Coverage

The first aspect is range or altitude above the surface of the Earth. As a general rule, close range is desirable for high resolution and active sensing; distant range is desirable for coverage and finer temporal resolution. Low Earth orbits enable observations of a given location or phenomena that repeat on the scale of days. Geostationary orbits enable observations on a scale of minutes, limited only by instrument cycle times rather than geometry.

Circular (or near circular) orbits provide constant range. Distant circular orbits provide synoptic coverage, with the most common being the geostationary orbit. Low Earth orbits (LEO) are used for improved resolution or to reduce active sensing (lidar/radar) power. In addition, a circular orbit can simplify the design and operation of instruments by maintaining near-constant range and rate of spacecraft motion over the surface of the central body, simplifying instrument scanning rates, etc.

The range to the observed subject affects the resolution, mass, and power requirements of active and passive electromagnetic instruments. At any given wavelength, diffraction limits the resolution of passive measurements as a linear effect of both the range to the subject and the telescope aperture. Doubling the telescope aperture can compensate for doubling the range, but this roughly results in a four-fold increase in telescope collecting area and an eightfold increase in telescope volume, with mass roughly scaling with volume. For active sensing, the transmitted power tends to drop off as the square of the distance, as does the return signal. Even small increases in range can require significant increases in transmitter power or receiver sensitivity.

In contrast, distant range is desirable for both broader spatial and higher temporal coverage, providing a synoptic view. In addition to high circular orbits, such as geostationary orbits, an approach to achieving near-constant distant range is to use highly eccentric orbits. Although the range varies widely, most of the time is spent near apogee. The most common example is the Molnoyia orbit. In addition, either the Earth/Moon or Earth/Sun Lagrange points can provide constant but distant locations.

To observe with very high temporal resolution the sensing vantage needs to be either within and supported by the Earth system (e.g., airborne or *in situ*) or else it needs to be distant. One of the interesting consequences of orbital mechanics is that even though increased orbital velocity raises the altitude of an orbit, the resulting rate of angular change relative to the central body decreases. Distant geostationary orbits enable constant, high temporal resolution observing.

To find the optimum trade-off between the advantages and disadvantages that scale with range, some missions select higher low Earth orbit (LEO) or medium Earth orbits (MEO). For example, when the Iridium constellation was first designed, it had 77 satellites (the atomic number of the element iridium). However, re-optimization of satellite coverage and power requirements resulted in the current configuration of 66 satellites. Despite the high radiation environment, MEO orbits are attracting increased interest as a compromise between required power and repeat coverage for active sensing missions.

B. Lighting and Time of Day

The second aspect of orbit value is lighting and local time of day of the observed subject. An orbit design can provide either similar or different lighting and time of day conditions. As a general rule for optical instruments, spatial resolution instruments prefer sun angles that enhance shadows for feature detection, while spectral resolution instruments prefer sun angles that reduce shadowing and enhance spectral contrast. Similar lighting and time of day conditions can ease the comparison of measurements by eliminating diurnal effects. However, this can lead to aliasing (e.g., if the subject of the observation has a significant diurnal dependence, such as afternoon thunderstorms). In these cases sampling across different times of day may be desirable. In addition to these direct effects on the subject, there may be other time of day effects on the area of interest that may influence the orbit design. These could be correlations with cloud or fog cover that interfere with the observation or differential warming rates and unstable ground temperatures for thermal emission instruments.

Two approaches for obtaining constant or near-constant lighting or time of day are close circular sun-synchronous orbits and the Sun/Earth Lagrange points. A low Earth orbit sun-synchronous orbit always crosses the equator at the same relative time of day. This is because the secular variation in right ascension of the ascending node matches Earth's rate around the Sun. Sun-synchronous low Earth orbits are highly inclined, retrograde orbits, usually near circular to negate any effect on the argument of perigee. These orbits are in common use for weather satellites and missions such as Landsat, IKONOS, Terra, EO-1, etc. More recently the Earth/Sun Lagrange points have been identified for what are called sentinel missions. These orbital positions provide constant lighting, but at astronomical distances.

Designing the orbit for constant, near constant, or slowly varying lighting can simplify the instrument design and operation, reducing the need to adjust or change instrument exposure or gain states, as well as more narrowly bound ing the aperture size needed to collect the light or the time required to collect adequate signal.

In contrast, some observations require variable lighting conditions. Any low inclination orbit, such as that of the Tropical Rainfall Monitoring Mission (TRMM) will span the entire range of times of day. The rainfall subject of TRMM benefited from this diurnal coverage. Similarly, the TIMED mission uses the same effect as sun-synchronous orbits, but with the opposite sign, so that the secular variation adds to the effect of Earth's motion around the sun. The orbit equatorial crossing moves from dawn to dusk four times per year. Distant circular orbits can provide variable lighting conditions. The most common is the geostationary (24 hour orbit period), which views a constant geolocation across all local times of day.

Even if the lighting conditions have no impact on the observation subject, missions may derive engineering benefits from considering the lighting and time of day of orbits. The orbit design can affect the spacecraft solar illumination as well as the reflected and thermal energy input from the Earth. These can be design considerations for missions with sensitive thermal or high power requirements. For example, a close sun-synchronous circular orbit with a 6AM/6PM equatorial crossing will remain in constant daylight, except for a short period around one of the solstices. In addition to providing continuous sunlight for power, these conditions keep nearly constant the direct solar thermal input as well as the reflected and emitted thermal input from the Earth.

C. Geocoverage/Geolocation

The third aspect of orbit value is geocoverage or geolocation. Spacecraft orbits are often designed for repeat ground-track. This can provide measurement subject benefits such as spatially correlated observations, the ability to directly compare observations of time-dependent phenomena, and more predictable operations such as repeat instrument state changes for land/sea boundaries, ground-station passes, etc.

A common example of a "repeat-track" orbit is a geostationary orbit. The one orbit per day results in constant geolocation. Other examples include the half-day orbits for Global Positioning System (GPS) satellites and Molnoyia satellites, the 8 day repeats (every 17 orbits) for the Russian GLONASS navigation satellites, or the 16 day repeats (every 233 orbits) for missions such as Terra, Aqua, etc.

As mentioned above, there is a correlation between distant range and near-constant geolocation. Distant range orbits can match or nearly match the Earth's rotation rate, enabling constant or near-constant geolocation. The most common example is the geostationary orbit with constant geolocation. Another example is the Molnoyia orbit. For Molnoyia orbits the apogee alternates hemispheres over a constant groundtrack, and the satellite remains over nearly the same geolocation for 11 hours per day.

III. Analysis of Orbit Value Trade Space

The following table summarizes these different aspects of orbit value, and includes examples for each combination.

Table 1: Orbit Value Trade Space

Range	Lighting/ TOD	Geo-Location	Example Orbit Types	Mission Examples
Close	Variable	Non-Repeat	Non-Repeating Non-Synchronous Orbits	ISS
Close	Variable	Repeating	Repeat Groundtrack Non-Synchronous Orbits	
Close	Similar	Non-Repeat	Non-Repeating Sun-Synchronous (Retrograde Polar) Orbits	
Close	Similar	Repeating	Repeat Groundtrack Sun-Synchronous Orbits	Landsat, Terra
Distant	Variable	Non-Repeat	GEO Transfer Orbits, MEO, HEO, Earth-Moon Lagrange	GOES
Distant	Variable	Repeating	Geosynchronous Orbits, Molnoyia Orbits	
Distant	Similar	Non-Repeat	Sun-Earth Lagrange Points, **Gap?**	DSCO
Distant	Similar	Repeating	**Potential Gap: ESSE Orbits?**	

IV. New Orbits and Vantages

The above table identifies a gap in capability for distant, near-constant lighting vantages. This motivates an examination of options to provide such vantages. Advances in technology may enable additional orbit and vantage options.

A. Eccentric, Sun-Synchronous, Equatorial Orbits

The search for distant observations with near-constant lighting suggests a possible new class of orbit, called here ESSE (for Eccentric, Sun-Synchornous, Equatorial) orbits. This type of orbit is similar to the Molnoyia and polar Sun synchronous orbits, and takes advantage of the orbit secular variations due to the Earth's oblateness (J2). ESSE orbits would precess such that apogee remains over a constant local time of day. For example, based upon modeling using the software package STK®, two satellites in phased equatorial orbits with periods of 5 hr. 20 min. 10 sec, eccentricities of 0.57, altitudes of perigee of 273 km, and altitudes of apogee of 17,976 km would always have one satellite with a local time of day at the sub-spacecraft point within about 2 hours 15 minutes of the constant local time of apogee.

Future work will consider if multi-day period, eccentric Earth orbits might use periodic interactions with the Moon to realign the time-of-day of apogee.

B. Continuous Thrust Technologies

New technologies for continuous or frequently repeated thrust may add options that are not sustainable based upon gravitational forces alone. Solar sails have been proposed to "bias" geostationary orbits towards more populated latitudes.[3] The technological innovations that would enable concepts for "pole-sitting" platforms are under study.

For the Sun-Earth Lagrange point vantages, continuous thrust technologies could expand the options as well. From the L-2 point, the angular size of the Sun is greater than that of the Earth, and observations from this vantage face the challenge of measuring the observation "signal" from the dark Earth while rejecting the much greater "noise" from the Sun. If a propulsion technology could sustain a spacecraft about 9% closer to the Earth than the L-2 point, this would enable observations from within the Earth's umbra. In addition, the Earth-Sun L-4 and L-5 points provide extremely distant observing vantages of approximately one astronomical unit. Constant thrust technologies could be used to sustain vantages that are substantially closer than the L-4 and L-5 points, enabling "dusk" and "dawn" sitters.

IV. Summary

This paper identifies key aspects of space-based vantages and suggests other vantages of possible interest for future Earth observation missions. The author hopes that an improved understanding of the value for Earth science of new vantages will facilitate the identification, development, and adoption of new technologies and capabilities that will help us to understand and protect our home planet.

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